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TECHNICAL REPORT

Criteria for the Selection of Microprocessor Combustion Controllers for Dual-Fuel Package Boilers

by
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In a typical package boiler, flue gas losses can account for 15 to 20 percent of the total heat released, and 20 to 25 percent of the fuel entering the boiler is lost. Boiler efficiency can be improved by minimizing excess air requirements within the level of safe and reliable boiler operation. However, until recently, combustion control equipment was too costly for installation and use with small package boilers.

This study surveyed manufacturers to identify combustion controllers appropriate for application to small package boilers. The survey revealed that "oxygen trimming" is the most common control method. Six manufacturers were selected for the final evaluation of three types of systems: (1) an in situ O_2 analyzer (2) an ex situ O_2 and combustibles analyzer, and (3) an air and fuel flow-metering device. The systems were reviewed and compared on the basis of ease of installation and maintenance, effectiveness, and cost.

Three commercially available combustion control packages were identified, one from each category, for a later field test demonstration. Three sites were selected for that demonstration. The results of such a demonstration could quantify the effects of state-of-the-art combustion control systems on the efficiencies of small package boilers.

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FOREWORD

This work was performed for the U.S. Army Engineering and Housing Support Center (USAEHSC), Fort Belvoir, VA, under the Facilities Engineering Application Program (FEAP), Work Unit EB-K11, "Microprocessor-Based Combustion Optimization for Package Boilers." The technical monitor was Mr. P. Conner, CEHSC-FU-M.

The research was performed by the Energy and Utility Systems Division (FE), of the Infrastructure Laboratory (FL), of the U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Noel Potts. Gary Schanche is Team Leader of the Fuels and Power Systems Team, CECER-FEP. Dr. David Joncich is Chief, CECER-FE. Dr. Michael J. O'Connor is Chief, CECER-FL. The USACERL technical editor was William J. Wolfe, Information Management Office.

COL Daniel Waldo, Jr., is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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CRITERIA FOR THE SELECTION OF MICROPROCESSOR COMBUSTION CONTROLLERS FOR DUAL-FUEL PACKAGE BOILERS

1 INTRODUCTION

Background

In fiscal year 1988 (FY88) the U.S. Army spent $432 million on heating operations, $172 million for natural gas fired operations and $175 million for oil. The Army goal is to reduce energy consumption during the 1985 to 1995 period by 8 percent on a Btu/sq ft-yr* basis in existing structures and by 10 percent on a Btu/unit produced in industrial processes.** The Army also plans to raise the productivity of its personnel (by providing energy systems that reduce adverse environmental effects), and to enhance energy security through dual-fuel capability. Unfortunately, installation engineering personnel typically have no time to investigate available types of energy savings or operation and maintenance techniques, or to decide where, when, or how to apply them. The Army has about 1300 boilers throughout the United States. About 90 percent of these burn oil or natural gas (alternatively, as required), and 10 percent burn coal. Although the Army operates about 75 central heating plants (CHP) with capacities between 30 and 300 MBtu/h, about 1100 smaller boilers in the 4 to 30 MBtu/h range serve small building clusters located off an installation's central heating network. These boilers are usually of firetube construction and burn Number 2 oil or natural gas. Because of their relatively small size, they are often overlooked in energy conservation programs.

Two basic objectives guide the design and application of a boiler control system:

1. To operate the boiler in such a manner so that a continuous supply of steam is provided at the desired pressure and temperature, and

2. To continuously operate the boiler at the lowest cost of fuel, consistent with a high level of safety and boiler design life.

The second objective deals with improving boiler efficiency in that achieving the lowest fuel cost involves operating under the most efficient combustion conditions. Automatic control systems actually operate the boilers, and whether the boiler achieves its optimum efficiency is a function of the capability of the other system components. Generally, control systems of greater sophistication are more precise and come closer to meeting control objectives, but at a higher initial cost than simpler systems.

In the past, sophisticated controls were so costly that they could only be justified for use with large industrial and utility boilers. As fuel costs rise (relative to fuel saving equipment costs), however, the savings in fuel cost resulting from the use of sophisticated controls on smaller boilers offsets the cost of the controls. Furthermore, the development of microprocessor controls and new sensors has helped to advance a new control concept aimed at even greater fuel savings at reasonable initial costs.

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* A metric conversion table is included on p 30.

** Department of Defense (DOD) Defense Energy Program Policy Memorandum 86-3.

Objective

The objective of this project was to identify equipment that maximizes boiler combustion efficiency by controlling the excess air in the flue of small package boilers.

Approach

A survey of control equipment manufacturers was conducted to identify state-of-the-art technology in combustion control systems. Three principal types of equipment were identified, and six combustion control equipment manufacturers were selected for final evaluation of their systems. The systems were reviewed and compared on the basis of ease of installation and maintenance, effectiveness, and cost. The system manufacturers were divided into three groups by type of control strategy. One manufacturer for each type of control was recommended for a later field demonstration, and three sites were selected for that demonstration.

Mode of Technology Transfer

It is recommended that the results of this study and subsequent demonstration be incorporated into Technical Manual (TM) 5-650, *Repairs and Utilities: Central Boiler Plants* (Headquarters, U.S. Army Corps of Engineers [HQUSACE], 13 October 1989), and Corps of Engineers Guide Specification (CEGS) 15561, *Central Steam Generating System, Combination Gas and Oil Fired* (HQUSACE, June 1989).

2 BOILER TECHNOLOGY

There are two general types of boilers: firetube and watertube. In addition, boilers are classified as high and low pressure, and as steam or hot water generating. High pressure boilers are steam boilers that operate at pressures greater than 15 psig. Low pressure boilers, operating below 15 psig, are almost exclusively used for space heating. This study did not consider watertube steam and hot water boilers since this project deals mostly with small to medium size, high pressure industrial firetube boilers.

Firetube Boilers

Firetube boilers constitute the largest share of the small to medium size industrial boiler market. The hot, flue gas products of combustion flow through and are cooled in the tubes of the boiler, which are surrounded by water. Most of the firetube boilers in use today are a modified Scotch Marine type boiler (Figure 1). Because of its design (completely water cooled), the radiant heat of combustion is directly transferred through the metal walls into the water, eliminating the use of refractory. The combustion chamber of the Scotch boiler becomes a very effective heat transfer surface because of the high temperature differential between the flame and the boiler water.

Two other variations of the Scotch boiler design are called "Wetback" and "Dryback," referring to the rear of the combustion chamber, which is either water jacketed or refractoried to protect it from overheating. Scotch boilers also differ in their number of "passes," or the number of horizontal runs the flue gases must take between the combustion chamber and the flue gas outlet. The combustion chamber is considered the first pass and each separate set of firetubes is considered an additional pass.

Performance

Boiler performance is the ability of a boiler to transfer heat from a fuel to water within the operating specifications, which include the boiler capacity and other related factors such as steam pressure, boiler temperatures and pressures, boiler draft, flue gas analysis, fuel used, and fan power requirements. The result of a performance specification for a given boiler is the calculated efficiency. Boiler efficiency is expressed as a percentage of the ratio of the heat supplied to the boiler and the heat absorbed by the water of the boiler. Boiler capacity is generally described in terms of boiler horsepower (BohP). Capacity rating specified in terms of pounds of steam per hour (lb/h) is also commonly used. Small firetube boilers are often rated in terms of maximum British thermal units per hour (Btu/h) input to the burner.

Operating Variables

Understanding boiler operating variables and their influence on the boiler's overall performance will help to identify the opportunities to save fuel. Several operating variables affect the overall performance and efficiency of a boiler:

- feedwater temperature
- steam pressure
- combustion air density
- boiler water quality
- waterside scale buildup
- fireside soot buildup
- boiler load.

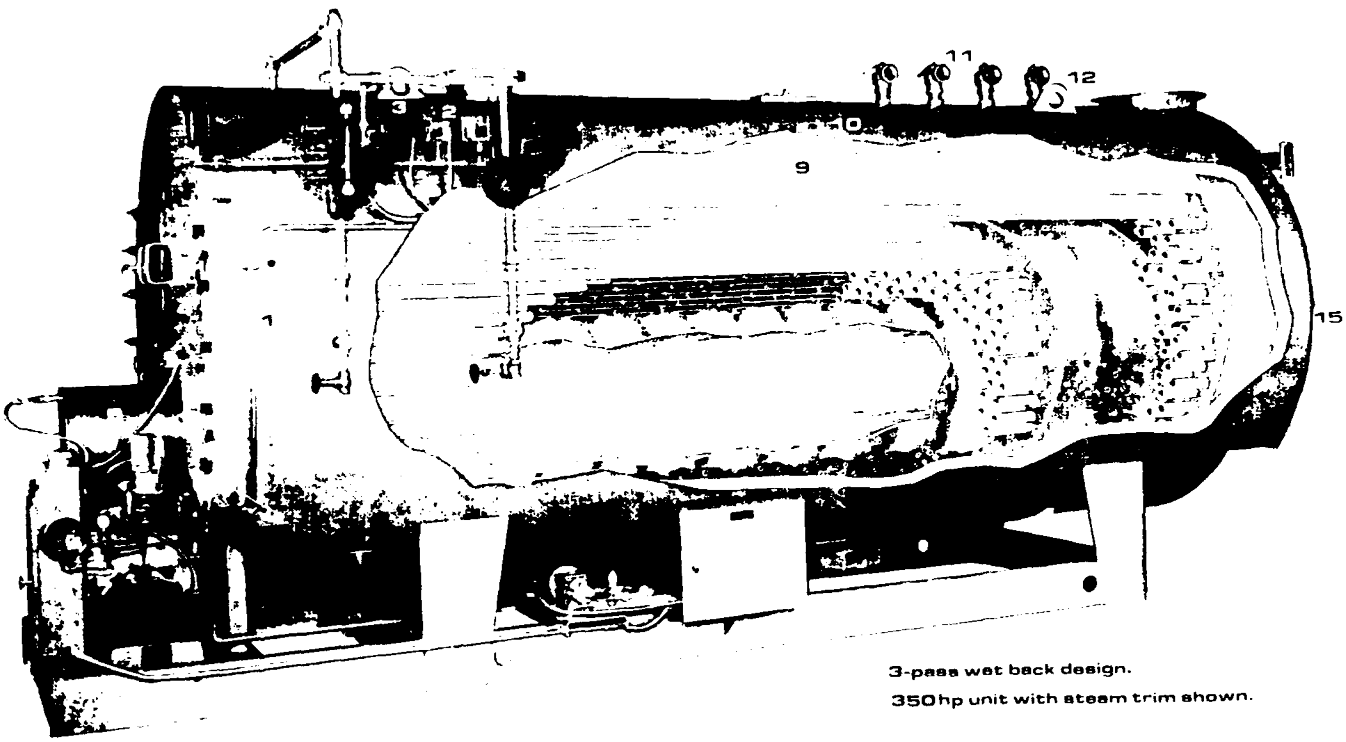

Illustration courtesy of Kewanee Boiler Corp., Kewanee, IL 61443.

Figure 1. Firetube Boiler.

The following is a list of several other operating variables that affect boiler performance and efficiency.

Flue Gas Temperature

Flue gas temperature is one of the key indicators of boiler efficiency. Higher flue gas temperature indicates a lower boiler efficiency because, when flue gas temperature is relatively high, more heat is lost to the stack. Conversely, lower flue gas temperature indicates higher efficiency because less heat is being lost when flue gas temperature is low. Differences in flue gas temperatures occur for several reasons:

- changes in air/fuel ratio
- soot deposits on fireside heat transfer surfaces
- scale deposits on waterside heat transfer surfaces
- change in boiler pressure
- air infiltration into boiler flue gas.

Excess Combustion Air

To assure complete combustion of a fuel, more air than the stoichiometric requirement must be supplied to the combustion process. This additional amount of combustion air is called excess air, which can be expressed in terms of the percent of oxygen measured in the flue of the boiler. A higher excess air level causes a reduction in flame temperature and a reduction in the boiler heat transfer rate. The effect of this change is an increase in the flue gas temperature and, therefore, a decrease in boiler efficiency. The amount of excess air in the combustion process depends upon the type of fuel, burner design, and other factors. An approximate amount of excess air required to achieve full capacity is as follows:

Natural Gas:	1.5 to 3 percent O_2 (7 to 15 percent Excess Air)
Fuel Oil:	0.6 to 3 percent O_2 (3 to 15 percent Excess Air)

Fuel Type

The type of fuel affects boiler efficiency primarily because of heat losses from the vaporization of water (latent heat loss) in the fuel and water formed through combustion of hydrogen. The amount of carbon in the fuel also affects efficiency, resulting in sensible heat loss. The greater the amount of carbon in the fuel, the greater the percentage of carbon dioxide in the flue gases; thus the greater the heat loss. Sensible heat loss increases in proportion to increased concentrations of carbon dioxide in flue gases. In general, the fuels with hydrogen have higher latent heat losses and fuels with carbon have higher sensible heat losses.

Combustion Air Temperature

Combustion air temperature also affects efficiency. (Note that the heat content of air increases as the air temperature increases.) The combustion air can be increased by recirculating the flue gase, or by using tubular air heaters. This way, the additional heat energy in the combustion air enhances the combustion process, and reduces the fuel requirements. In general, 1 percent of the fuel is saved for each 40 °F rise in combustion air temperature.

3 COMBUSTION CONTROL STRATEGY

The combustion control system determines how a boiler actually operates and whether it achieves, together with the feedwater controls, its efficiency potential.

Generally, the controls can be classified into two main groups: on/off and modulating. The on/off group can be further subdivided to full-fire on/off and high-fire/low-fire/off, and the modulating controls are subdivided into two basic groups: positioning and metering.

On/Off Control

The on/off control is the most basic and least costly of the burner controls. Its use is typically limited to controlling the firing rate on small firetube boilers. Boiler startup is initiated by steam pressure or temperature drop. The flame remains on at full firing rate until the pressure or temperature reaches its preset limit. Although the system may maintain the steam pressure within acceptable limits, combustion is not controlled; combustion efficiency is a result of mechanical burner adjustment. In addition, during the burner off time, cold air passes through the boiler carrying heat up the stack. The high-fire/low-fire/off system has an advantage over the full-fire on/off system in that it has two firing rates. As long as the steam demand stays between the high and low fire requirements, the burner will remain on. This system will hold the steam pressure or the temperature within closer tolerances and can be tuned to burn the fuel efficiently. Since the adjustments of the air/fuel ratios are provided by mechanical linkages, some compromise may be necessary in optimizing combustion at both the high and low fire.

Modulating Control

The modulating control system represents an improvement in the control of the combustion process. A continuous control signal from a controller connected to the steam line is matched to the burner output; reduction in steam pressure or temperature increases the signal, which then calls for an appropriate increase in firing rate.

Positioning Systems

Two modulating system types, most widely used on firetube boilers, are the single-point positioning system and the parallel positioning system. The single-point positioning (jackshaft) control (Figure 2) works on the principle that the fuel valve and the air damper are operated from a single source (master regulator) through a series of cams and linkages. The system is set up under a test condition to operate the boiler as efficiently as possible over the load (firing) range. Since no sensors are incorporated in the system, any variations in air and fuel supply will result in a loss of boiler efficiency. To avoid such situations, the system is adjusted for higher excess air to create a wider control error band.

In the parallel positioning system, the air damper and fuel valve are not mechanically linked together but, rather, are connected independently through pneumatic or electrical circuits. Since the fuel valve and the air damper are driven individually, the system can be adjusted for better, more efficient operation during the setup test run. As in the single-point positioning system, no sensors are used. Since any changes in the condition of the air and fuel will not be compensated for, it is typical for such systems to be adjusted for higher excess air operation to prevent unsafe fuel-air ratios.

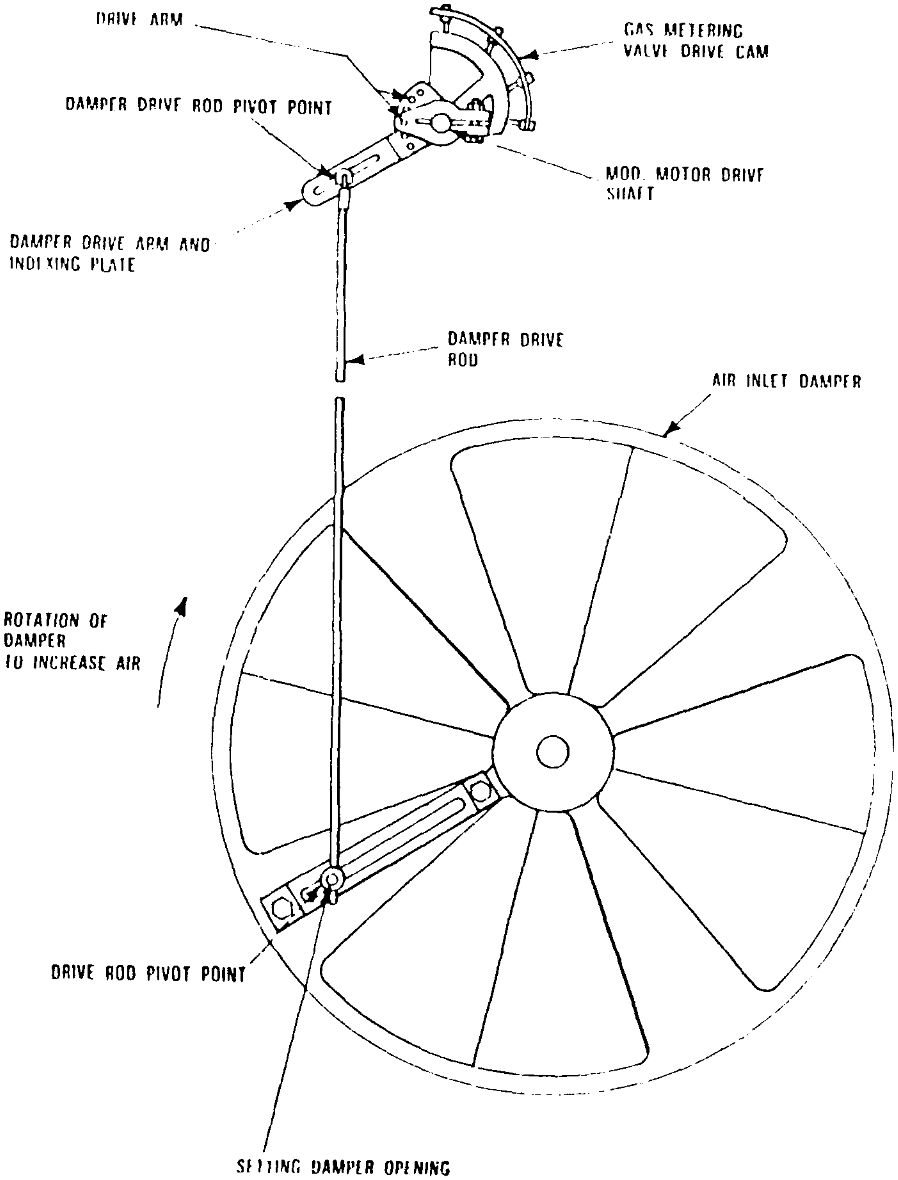

Figure 2. Single-Point Positioning Control System.

Table 1 compares these control systems' achievable efficiency. Although each boiler has its own characteristics of excess air versus flue gas temperature, the table is typical for a gas fired boiler with flue gas temperatures of about 450 to 600 °F. The influences of changes in the fuel and air have been minimized by assuming 10 percent excess air (2.2 percent excess O_2) in the flue gas. Table 1 reveals the following.

1. At 25 percent load, two categories the high-fire/low-fire/off and the modulating control systems have the same efficiency.

2. At 100 percent load, all systems would be "on" full time and, therefore, results are the same for all systems.

Table 1

Control System Performance

Type of Control	Efficiency at % Load 25%	50%	75%	100%
On/Off	70.28	74.28	75.61	76.28
High/Low/Off	76.88	76.48	76.35	76.28
Modulating	76.88	77.68	77.15	76.28

3. In the middle range (50 and 75 percent load) efficiency improves as the type of control becomes more sophisticated.

In general, the operation of a positioning control as well as a metering control system can be improved by adding an excess air trim control system to the existing basic equipment. (Chapter 6 gives further detail.) Excess air trim control can be applied to either the air or fuel control. One way of applying the trim control is to add a mechanical linkage so that the "percent of excess air" can be adjusted with the air damper without changing the fuel flow.

Metering Systems

A metering type control system is better suited for boilers with relatively fast changing steam loads where the fuel and combustion air flows are monitored by sensors. The use of sensors eliminates approximately one-half of the errors caused by the changes in the combustion properties of the fuel and air (as compared with a positioning system). The metering control system contains an important safety feature not present in a positioning (either single point or parallel) control system, called "cross limiting." In this system, the safe mixture of fuel and combustion air is assured by preventing the presence of fuel in excess of the desired combustion air flow. This feature is particularly valuable when the boiler steam load is changing rapidly. As with the positioning control system, the operation of the metering control system can be improved by adding the excess air trim control system to the existing basic equipment.

Excess Air Trim Controls

The objective of an excess air trim control system is to operate the boiler with a minimum of excess air. The most common combustion control systems used on the firetube boilers do not compensate for the variables in fuel and air supply that can affect the fuel/air ratio. Therefore, combustion air is set up so that enough excess air is available for the complete combustion of the fuel under any load. It is this excess air that creates inefficiency. Figure 3 shows the relationship between the excess air and fuel. The higher the excess air, the greater the energy loss, and consequently, the greater fuel and dollar loss. For a given boiler configuration, there exists a zone of maximum combustion efficiency. The excess air trim control should keep the boiler operating in this zone of maximum efficiency.

In minimizing excess air at the burner, measuring oxygen in the flue gas is the most direct approach. This is a direct excess air measurement because there is an exact correlation of oxygen to excess air for all fuels. Oxygen measurement by itself, however, cannot detect poor combustion (fuel/air mixing), burner malfunction, smoking, or other undesirable conditions. Also, in practice, oxygen measurement is subject to a number of conditions that may result in inaccurate indication of excess air levels. These include:

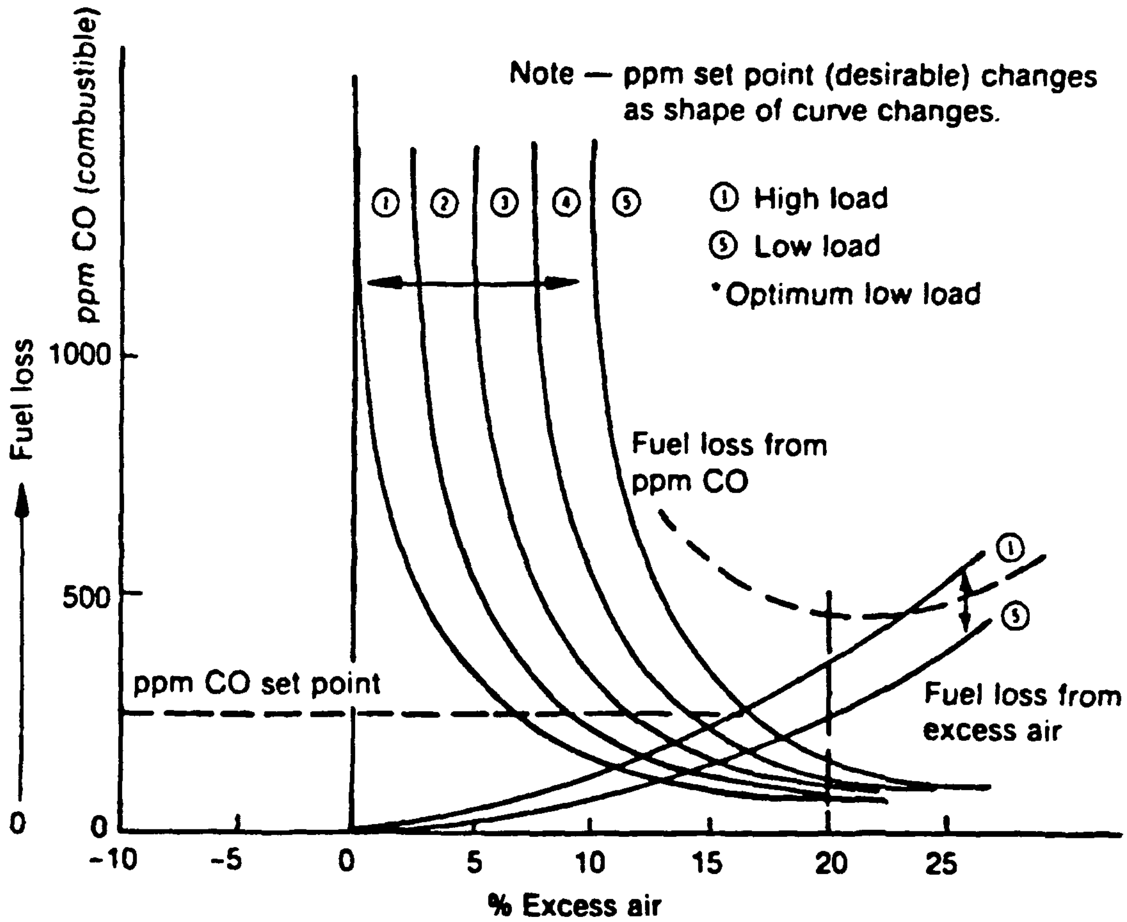

Figure 3. Excess Air-Combustible Gas Relationship.

1. Air Leakage: Oxygen concentration in the stack gas could be diluted by leakages that enter the boiler downstream of the combustion zone, resulting in higher oxygen readings.

2. Flue Gas Stratification: Since oxygen measurements are usually taken at a single point in the flue, stratification can lead to inaccurate oxygen indication.

3. Sensitivity: At low excess air conditions, the oxygen levels make the control difficult due to the insensitivity of the instrument near its zero point.

Therefore, CO levels in the flue of the boiler can be used to cross check oxygen measurements and compensate for some of the deficiencies in the oxygen measurement techniques. Although CO measurement is not an index of excess air, it is a good indicator of the completeness of combustion and, therefore, of fuel/air mixing, burner malfunction, and smoking problems. However, CO measurements are affected to a lesser degree by the dilution of flue gases through air leakage. In addition, at low excess air conditions, CO instrumentation sensitivity is high; the concentration of CO in the flue gas increases rapidly with lower excess air, yielding conditions for sensitive carbon monoxide measurement. Thus, the combination of oxygen and carbon monoxide measurements incorporated into the excess air control package will provide the best technical approach to monitoring and keeping boiler operation in the zone of maximum combustion efficiency.

4 AUTOMATIC COMBUSTION TRIM CONTROL PACKAGE

The automatic combustion trim control package most widely used consists of three independent subsystems: a flue gas analyzer, a microprocessor-based controller, and an actuator.

Flue Gas Analyzers

Several flue gas analyzers are potentially useful in combustion trim control. These analyzers are used individually or in combination, based on the type of trim control desired. This discussion concentrates on two of the constituents of the flue gas: oxygen (O_2) in percent range and total combustibles (CO) in the parts per million (ppm) range. Two methods most commonly used to obtain flue gas analysis are the "in situ" and "ex situ" (extractive) methods.

"In Situ" Method

The in situ method uses an analyzer probe inserted into the flue at the point of analysis. The measuring cell for obtaining the oxygen is zirconium oxide-based. The cell reacts to the ratio of partial pressure of oxygen in the flue to the partial pressure of oxygen in the reference air brought to the cell from outside. Response time of these analyzers is 5 to 10 seconds. For the results to be accurate and repeatable, the cell temperature is closely monitored and held in the 1300 to 1600 °F range. Because of the elevated temperature of the cell, residual combustible gas is burned in the cell using some of the oxygen in the flue. The result is, therefore, a net percent O_2 measurement that includes the oxygen consumed by the combustion of the residual combustible gases. The cell output is processed by inversion, linearization, and amplification to produce a linear signal of percent O_2 versus milliamps (mA). In this form, the signal can be used by many standard control instruments.

"Ex Situ" or Extractive Method

In the ex situ method, a small sample of the flue gas is drawn (extracted) from the flue to the heated cell housing mounted on the flue wall. Response time depends on the method of sample extraction. With the air-aspirated sample, the response time is in the range of 10 to 15 seconds. When natural or thermal aspiration is used, the response time extends to 25 to 40 seconds. The ex situ method is applicable to the measurement of net percent O_2 and parts per million (ppm), or percent combustibles.

If O_2 is being measured, the measurement principle is the same as that of the in situ method. In this case, however, the temperature-controlled zirconium oxide cell is located in the cell housing mounted on the outside of the duct. With this method, the flue gas temperature can be more than 3000 °F. The measurement signal and its processing functions are, again, the same as with the in situ method.

If total combustibles are being measured, a catalytic type of sensor is used. The remaining combustible gas present in the flue gas is burned on the sensor, causing it to produce a signal. The signal is then amplified to that of standard measuring instrumentation. The transport of the flue gas sample to the sensor is identical to the gas transport for O_2 measurement. The cell is housed in the same assembly as for the O_2 cell and the same flue gas sample is usually used.

Microprocessor-Based Controllers

A microprocessor-based controller is a package of control loops and functions into which a number of inputs are connected, and from which a number of outputs are delivered to the final control devices. The microprocessor evaluates the incoming primary variables and incorporates them into certain computations that then determine the magnitude and direction of change to the manipulated control device. For example, the signal(s) from the flue gas analyzer(s) are connected to the inputs of the controller where they interface with calculated variables to produce the trim action required to achieve the optimum fuel/air ratio.

Today's technology allows for many control advantages to be obtained by using the microprocessor-based controller. Different manufacturers offer different options with their controllers. Items to consider when selecting a new controller include:

- boiler size
- number of boilers to be operated
- normal loads and load variations
- rate of load change
- type of fuels
- existing measurement devices
- final control elements.

Also important are the interactions between the individual loops of the controller:

- bumpless transfers between the individual controlling loops
- bumpless transfers between auto/manual modes
- verification of control signals
- isolation of input signals
- fault diagnostics
- fail-safe action when fault occurs
- adaptability to changing conditions of the boiler
- safety of the control system.

Actuators

A processed signal (output) from the microprocessor-based controller is sent to an actuator. The actuator is the final controlling element of the system, connected to the air damper or fuel valve. The actuator adjusts the damper or fuel valve based on the signal from the microprocessor. The actuator should be of an uncomplicated, rugged design and should provide for positive positioning of the dampers and valves without slippage, distortion, or linkage "slop." Commercially available actuators vary in size, mechanical design, output torque, and manner of incorporation (linking) with the existing control components. Actuator designs should be closely inspected to ensure that they are of dependable design and appropriate size for the application.

5 COMBUSTION CONTROL SYSTEMS SURVEY

The objective of the control systems survey was to identify commercially available combustion control systems with the potential for cost effective improvement in boiler operation when installed on existing Army firetube boilers (100 to 500 hp). The essence of the project was to reach the majority of the manufacturers in the United States and abroad to obtain information on the state-of-the-art in boiler combustion controls. The literature received was then evaluated and a recommendation was made on the selection of three microprocessor-based combustion control systems for field testing. Several basic specifications guided the evaluation and selection of the controllers:

- cost effectiveness
- installation requirements
- maintenance
- principle of operation
- commercial availability.

Manufacturers Survey

The initial task of the survey involved preparing the list of potential controller manufacturers and a form letter which, together with the control specification, was mailed to the manufacturers. All responses to the letter of inquiry were reviewed and assessed. The positive responses were selected for further consideration. The appendix to this report lists the surveyed manufacturers.

Survey Results

A total of 37 manufacturers were approached during the survey. Of these, 15 manufacturers (42 percent) answered our request. Several of the answers were in duplicate since several of the manufacturers used components (analyzer or actuator) in their control package made by other manufacturers that also replied to our survey. Some of the responses to our survey came from control suppliers representing several different manufacturers and, therefore, duplicated manufacturers responses. After the responses were reviewed, six companies were selected for further evaluation.

Control Systems Selected for Evaluation

The six control manufacturers selected for further evaluation are listed in Table 2. The following is a short description of each system, based on the literature received and contact with the manufacturer.

Ametek, Thermox Instruments Division

The Ametek system is composed of an ex situ oxygen analyzer with an optional combustibles monitor, a microprocessor-based controller, and a trim control actuator. The oxygen analyzer is an extractive type zirconium oxide unit mounted directly on to the outside of the stack. A continuous stream of flue gas flows by convection through the inlet probe and past the heat sensor before it is returned to the stack. When a separate measurement of unburned combustibles is required, a catalytic combustibles detector is installed in the flue gas flow loop. The maximum flue gas operating temperature of this instrument is 1300 °F. Accuracy of the sensor is ±2 percent of the measured value. The analyzer does not require any sample conditioning and the unit is field serviceable. The response time of the sensor is 37 seconds to

Table 2

Control System Manufacturers Selected for Evaluation

Ametek Thermox Instrument Div. 150 Freeport Road Pittsburgh, PA 15238 412/828-9040	Dynatron Inc. Energy Conservation Systems Barnes Industrial Park P. O. Box 745 Wallingford, CT 06492 203/265-7121
Century Controls, Inc. 750 South Plaza Drive St. Paul, MN 55120 612/454-0792	Syconex Corp. ETC Division 433 W. Allen Avenue San Dimas, CA 91773-1443 714/592-5684
Control Techtronics, Inc. 99 S. Cameron Street Harrisburg, PA 17101-2805 717/238-0405	Westinghouse Electric Corp. Combustion Control Division Orrville, OH 44667 1-800/628-1200, Ext. 658

reach 90 percent of step change. The microprocessor is a time-based on/off controller. The controller output operates the actuator for a predetermined amount of time (on), and then stops and waits (off) for another preprogrammed period. The controller can be programmed for two separate fuels (natural gas and oil). Each fuel is individually characterized by five adjustable potentiometers. In addition, the microprocessor has several other features: a high and low oxygen alarm; an automatic/manual control selector; a feature that will not allow O_2 level to decrease below 0.5 percent; and a feature to automatically increase the air (about 15 percent) when an analyzer problem is detected. The mechanical actuator is designed for boilers with jackshafts or other mechanical, parallel air/fuel positioning systems. It weighs 16.5 lb and its overall size is 17-1/2 in. long x 4 in. wide x 10-1/4 in. high. The actuator develops 40 to 100 lb of force. Its speed of travel is 60 seconds from minimum to maximum correction.

Century Controls, Inc.

Century's system uses Ametek's oxygen analyzer with the optional carbon monoxide sensor. The microprocessor-based controller and actuator is made by Century Controls. The microprocessor is available as an expendable control that can trim up to 5 boilers or that can be scaled down for 1 or 2 boiler applications. It contains all the standard options and in addition, numerous other parameters can be keyed in to match the distinguishing characteristics (speed of response, fast and find trim, etc.) of each individual boiler. The company is very flexible in its approach of control design and is willing to work with the customer to develop a control package to fit specific requirements. The actuator is applied as a retrofit to the jackshaft linkage. It has adjustable thrust (5 to 40 lb), and zero backlash problems since gears are not used. The actuator weighs 5.5 lb and can be easily and quickly installed.

Control Techtronics, Inc.

The control package offered by Control Techtronics is based on matching the oxygen levels to the varing fuel flow as required by the combustion process. The microprocessor takes input from differential pressure transducers located in the air and fuel lines. It then modulates the fuel flow to minimize excess oxygen based on a preprogrammed calibration curve (air/fuel ratio) made of eight points. Monitoring the air and fuel flow to the boiler, therefore, eliminates the need for the use of an oxygen analyzer. The controller can be independently programmed for two fuels (natural gas and oil) and can provide simultaneous and independent operation of up to four boilers. When installing this control package on a jackshaft operated boiler, the jackshaft is removed and a separate motor drive is installed to operate the air damper.

Dynatron Inc.

Dynatron uses an in situ oxygen analyzer coupled with a Preferred/Rimcor trim controller and actuator. The in situ oxygen sensor is a solid state, zirconium oxide fuel cell. At 2 percent oxygen concentration, the sensor is accurate to within ±0.1 percent O_2. Maximum stack gas temperature is 1400 °F (760 °C) and response time is 18 seconds to reach 63 percent of the reading, and 30 seconds to reach 95 percent of the reading. The sensor is field serviceable and a manual calibration kit is supplied as standard. The microprocessor is a single loop configuration controller with a primary output of 4 to 20 mA DC. Two additional outputs can be provided for recording and secondary control purposes. A 10-point function generation is provided to calibrate the controller to the oxygen versus load curve for the specific boiler. The microprocessor includes an 8-point annunciator. The front panel consists of keyboard, display, and LED bargraphs. The actuator is a fully self-contained, electromechanical differential actuator. The input and output shafts can be differentially positioned by an internal vernier motor. An electric drum brake prevents the actuator from overtravel. Potentiometers driven from input and output shafts provide for position feedback. The entire mechanism is submerged in oil.

Syconex Corp., ETC Division

The ETC control package consists of an in situ, zirconium oxide oxygen analyzer, a central processor unit (microprocessor), and a trim unit (actuator). The (Series 2000) package was developed in Europe by ETC Ltd., which is the subsidiary of the Syconex Corp.

The Series 2000 System uses a 16-point, self-learning, adaptive trim control technique that adjusts the air/fuel ratio for optimum combustion and monitors flue gas temperature, oxygen level, air damper, and fuel valve. The system has the capacity to control dual-fuel applications. The hardware includes a combustion air temperature sensor and burner control interface unit. The motor drive, which drives the damper actuator, is of flexible cable design. The damper actuator can be selected from six different types, the smallest having a length of only 3-1/2 in.

Westinghouse Electric Corp.

Westinghouse's trim controller (Veri Trim) includes an in situ oxygen analyzer, a microprocessor based electronic control unit, and an electromechanical actuator (Veri Link). The analyzer is equipped with a zirconium oxide type cell. The accuracy of the sensor is ±0.2 percent O_2. The microprocessor is proportional, integral, derivative (PID) configured for constant loop gain. The output is (optionally) 24V DC pulse (increase/decrease) or 4 to 20 mA. Trim action is limited by preset high/low limits. The excess air versus load curves can be programmed into the controller for two different fuels (natural gas and oil). The alarm points are dedicated for high/low O_2 setpoint deviation, probe failure, and actuator failure. Two auxiliary outputs are provided for use with indicators or recorders. The trim actuator is a cable that runs to the remotely placed (3 ft) actuator motor. It develops 20 lb of thrust and travels at the speed of 1 in. in 30 seconds. The Veri Link replaces the original air damper connecting link. Its size is 1.5 x 2 x 7 in.

Survey Summary

All six manufacturers evaluated for this study met the specifications set forth. The systems are commercially available, have similar installation requirements, and (except for one system) use similar principles of operation. The single exception (Control Techtronics) uses combustion air and fuel flow metering as the primary input for the microprocessor rather than an oxygen/combustibles analyzer used by the other manufacturers.

The reliability of the control systems and consequently their maintenance requirements can be evaluated only in general terms. It can be predicted that the sensor assembly of the oxygen analyzer is the component of the control package most "prone to fail." The other components of the package should be mechanically reliable, subject to a normal rate of failure.

Table 3 shows the costs of the control packages as quoted by the manufacturers/suppliers. The prices do not include the costs associated with component installation, nor do they include any manufacturers' assistance cost during startup. The table is divided into three categories by type of analyzer or of primary input for the microprocessor-based controller.

Table 3

Price Quotes From Manufacturers and Suppliers

Type of Control	Manufacturer/Supplier Name	Price
In Situ O_2 Analyzer	Dynatron Inc.	\$ 8,345.00
	Westinghouse Corp.	\$ 7,296.00
	Ametek	\$ 7,000.00
	Syconex Corp.	\$ 8,626.00
Ex Situ O_2/Combustibles Analyzer	Century Controls, Inc.	\$ 9,045.00
	Ametek	\$12,000.00
Combustion Air and Fuel Metering	Control Techtronics, Inc.	\$ 5,000.00

6 ECONOMIC ANALYSIS

It is important to calculate the financial value of any technology that improves the efficiency of a boiler to determine if the added value will offset the cost of implementation. One way to measure this benefit is by computing the extra or marginal output produced by the technology. The dollar value of this extra output can be calculated by multiplying the marginal Btu/yr by the cost per unit of fuel.

For high efficiency boiler technology, this value translates into lower fuel costs resulting from increased output. Calculations were performed for three different fuel prices (Figures 4 through 8) to illustrate the impact on the analysis of rising or falling fuel costs. The Btu/yr output of a boiler can be estimated by Eq 1.

$$\begin{aligned}\text{Btu/yr} = {} & \text{Efficiency factor}(\%) \times \text{Boiler size}(\text{hp/hr}) \\ & \times 365\,\text{days} \times 24\,\text{hours} \times \text{Load factor}(\%)\end{aligned} \qquad \text{[Eq 1]}$$

The extra boiler production results from the higher efficiency factor in the equation above. The fuel cost savings produced over a given time span can be compared to the initial cost of the technology. One way to do this is to estimate a discounted payback period requirement that must be met for the technology to be acceptable. A payback period represents the amount of time (in years) that a project requires to recoup the initial investment (i.e., to break even). All benefits occurring beyond the payback period date are considered to be profit. The payback period is computed by dividing the cost of the project by the dollar return per year. A discounted payback period introduces the interest rate to force the analysis to consider the "cost of money." This reflects costs associated with borrowing the funds needed to finance the project, or the opportunity cost of being unable to invest these funds for a given rate of return. The (arbitrary) discount rate used throughout this analysis is 10 percent.

This analysis requires a 3-year discounted payback period to repay costs. Figures 4 through 8 show "percent additional boiler efficiency" on their horizontal axes and "3-year payback value" on their vertical axes. To measure the value of a 5 percent gain in efficiency, for example, locate 5 percent on the horizontal axis and the appropriate fuel cost curve, and then use the vertical axis to locate a dollar amount (in thousands). This amount represents the cost that must not be exceeded by the technology to produce a 3-year discounted payback period. In other words, given a 10 percent discount rate and a 3-year payback period, no more than the corresponding dollar amount marked on the vertical axis can be spent to achieve the corresponding percent efficiency gain marked on the horizontal axis. Figures 4 through 8 show that, as fuel becomes more expensive, the dollar value of the technology rises. Also, as load factors increase, so does the value of the technology. Finally, the value of the technology increases linearly with the horsepower of the boiler.

Although this analysis accurately captures the cost associated with fuel savings, it does not address such issues as emissions, differential operating and maintenance costs, and service life impact associated with the technology. These factors may contribute positively to the benefits from implementing such a technology, and must be examined along with fuel savings considerations to determine an overall project acceptability.

The value of the microprocessor boiler control under consideration can be determined by comparing the estimated capital cost of the system to the expected fuel savings as predicted by the boiler efficiency analysis. Table 4 lists quotes from the selected manufacturers for this equipment.

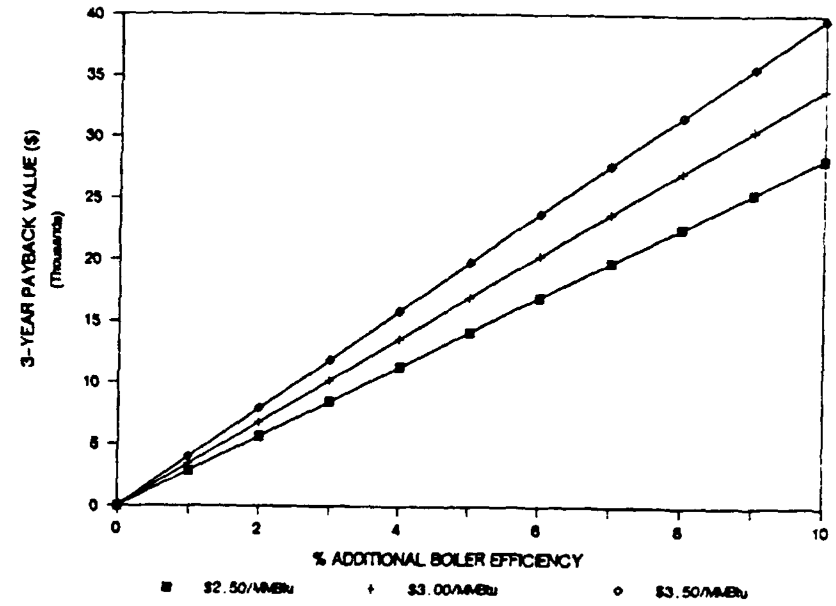

Figure 4. Value of Increased Boiler Efficiency at 65% Load, 200 hp, 76% Efficiency.

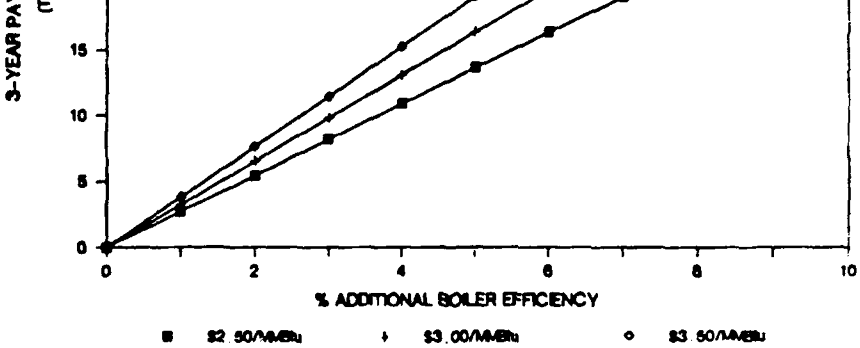

Figure 5. Value of Increased Boiler Efficiency at 50% Load, 250 hp, 76% Efficiency.

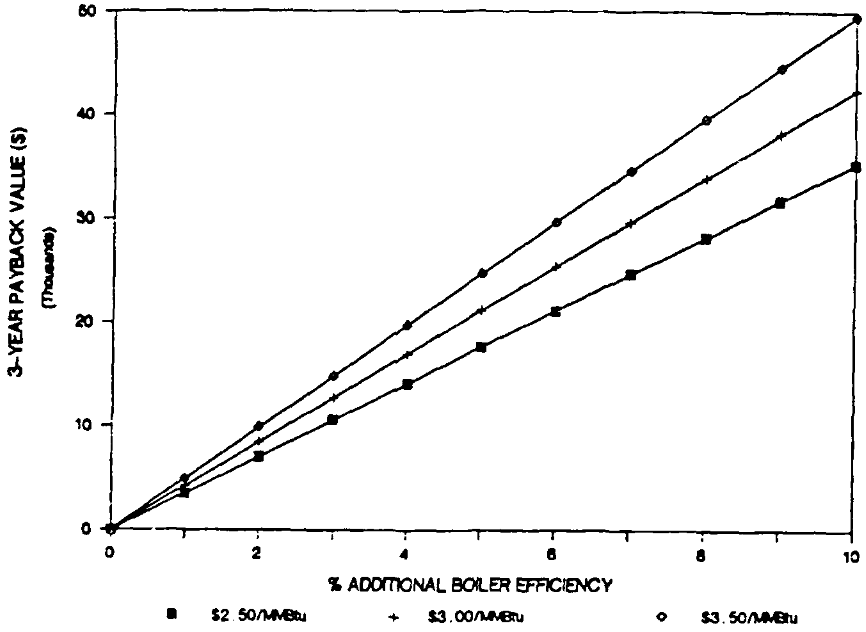

Figure 6. Value of Increased Boiler Efficiency at 65% Load, 250 hp, 76% Efficiency.

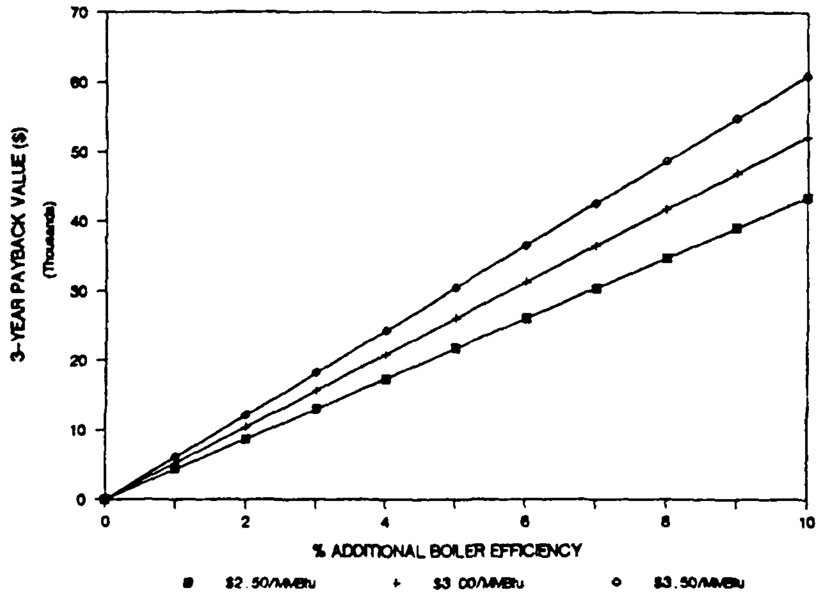

Figure 7. Value of Increased Boiler Efficiency at 80% Load, 250 hp, 76% Efficiency.

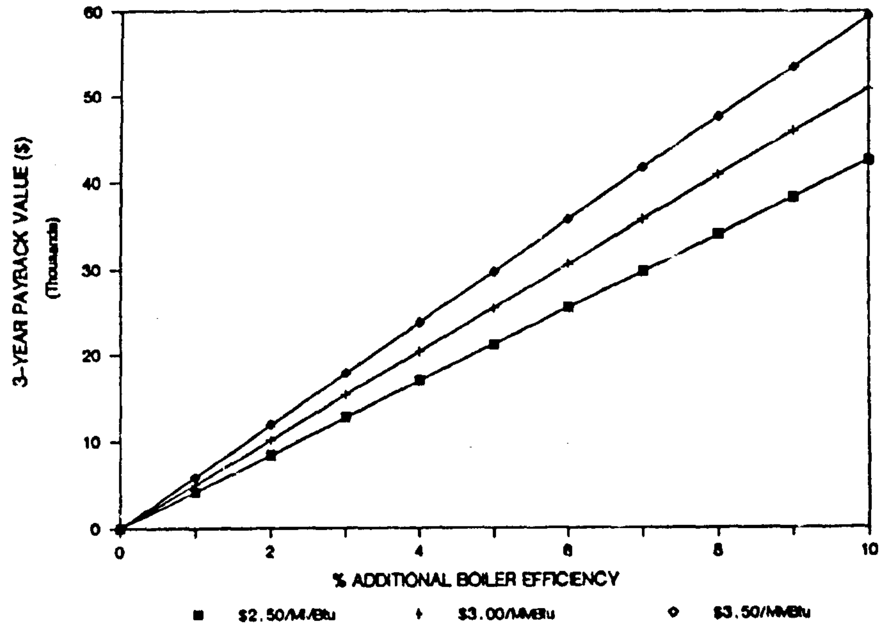

Figure 8. **Value of Increased Boiler Efficiency at 65% Load, 250 hp, 76% Efficiency.**

Table 4

Price Quotes From Selected Manufacturers and Suppliers

Manufacturer/Supplier Name	Package	Price
Century Controls, Inc.	Ex Situ CO_2/Combustibles Analyzer	$ 9045.00
Control Techtronics, Inc.	Combustion Air and Fuel Metering	$ 5000.00
Westinghouse Electric Corp.	In Situ O_2 Analyzer	$ 7296.00

Installation for this equipment is estimated to cost approximately $2000. Thus, the installed capital cost for this equipment ranges between $7000 and $11,000. Plotting this cost data against the boiler efficiency graphs in Figures 4 through 8 shows that the project is largely acceptable. The figures also predict a 2 percent improvement to be worth between $6000 and $10,000 depending upon the cost of fuel under conditions of a 3-year maximum payback. This assumes a 65 percent load factor and a 250 hp boiler.

Moving to a 5-year payback period produces an acceptable expenditure range of $10,000 to $15,000, while implementation of microprocessor controls allows a 2 percent improvement to be worth $8000 to $12,000 on a 300 hp boiler and $6000 to $8000 on a 200 hp boiler for a 3-year payback. Should the load factor on a 250 hp boiler increase to 80 percent or decrease to 50 percent, the acceptable expenditure range would change to $9000/$12,000 or $5000/$7000.

7 FIELD TEST SITE SELECTION AND PREPARATION

Researchers visited the three sites identified by USACERL to investigate the potential for field testing of the selected combustion control systems. These sites are located at Yakima Training Center, WA; Fort Knox, KY; and Louisiana Army Ammunition Plant, Shreveport, LA. Each site had three identical boilers, of which the first was to be tested in original configuration; and the second with the new combustion control.

Yakima Training Center (YTC)

The boiler house at Plant 223 at YTC contained three identical, relatively new (installed in 1987), Kewanee Classic III 300 hp boilers arranged as shown in Figure 9. All three boilers were equipped with Kewanee Series F dual-fuel package burners for firing natural gas or No. 2 oil. The boilers were also equipped with oil meters and Westinghouse O_2 trim controls.

Based on the system design and boiler arrangement, the Westinghouse O_2 trim control was tested on boiler No. 2 and the new burner on boiler No. 1. Preparations at the boiler house for field testing included the following major items:

1. Updating the Westinghouse O_2 trim control on boiler No. 2 per manufacturer's specifications
2. Restoring boiler No. 3 to original configuration per Kewanee specifications
3. Installing individual gas flow meters and a total oil flow meter
4. Modifying the steam piping to allow steam venting
5. Providing an opening in the stacks for boiler exhaust gas temperature and emission monitoring
6. Cleaning all boilers.

Fort Knox

The boiler room in Building 1483 at Fort Knox had three identical Kewanee Classic III 200 hp steam boilers manufactured in 1979. The arrangement of the boilers is shown in Figure 10. The boilers were equipped with Kewanee Series F package burners. Boiler No. 3 was set up for gas firing with no oil train, whereas boilers No. 1 and No. 2 were set up for oil firing with no gas trains. The new Control Techtronics combustion ratio controller was tested on boiler No. 3; and test boiler No. 1 was left with its original burner/control configuration.

Field tests of the Control Techtronics controller included the following major preparatory work:

1. Adding gas train to existing oil-fired burner on boiler No. 1
2. Adding oil train to existing gas-fired burner on Boiler No. 3.
3. Installing the ratio controller on boiler No. 3 per manufacturer's specifications
4. Installing main and individual oil flow meters
5. Installing main and individual gas flow meters
6. Modifying steam piping to allow steam venting
7. Providing openings in stacks for temperature and emission monitoring
8. Cleaning all boilers.

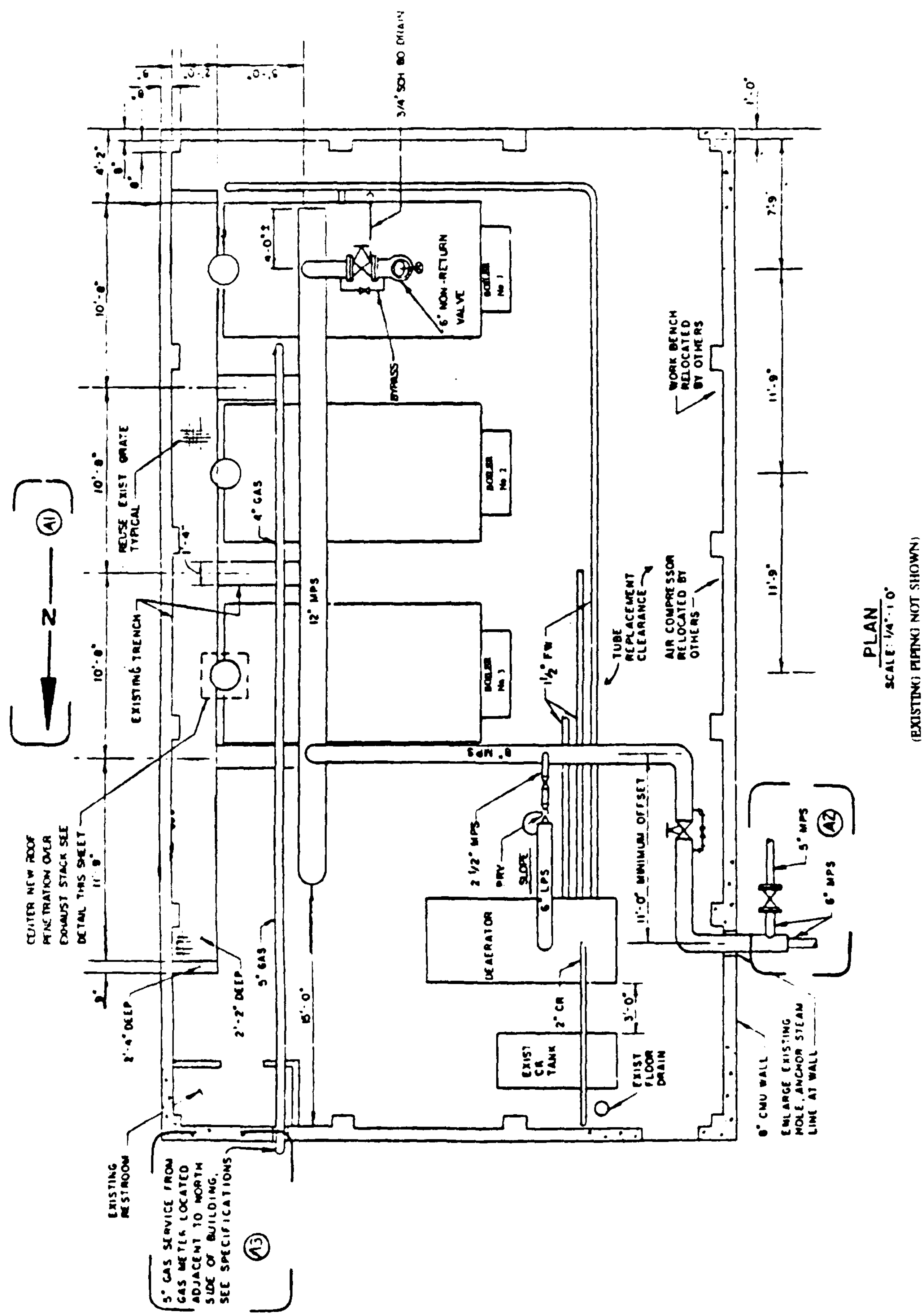

Figure 9. Boiler Arrangement at Yakima Training Center.

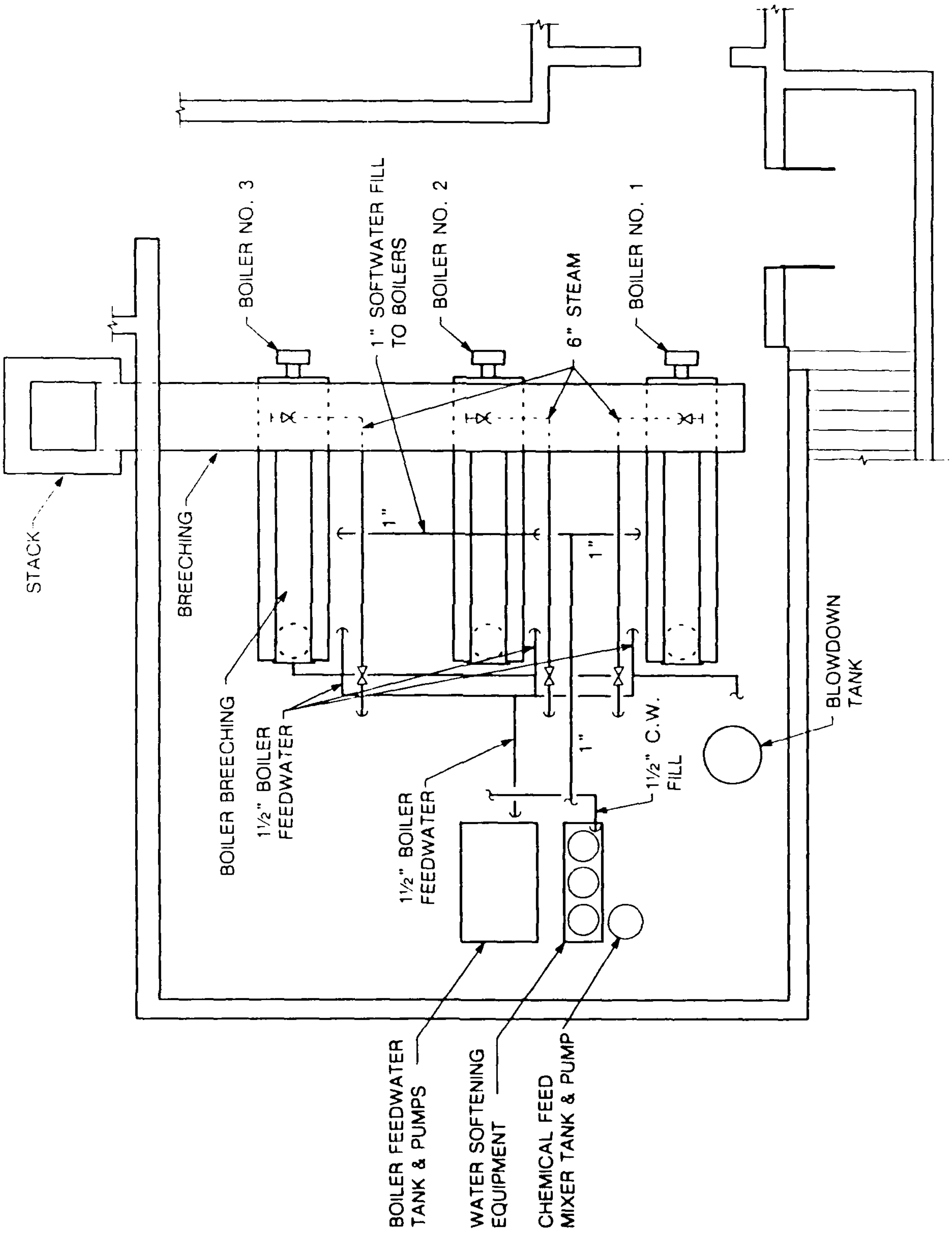

Figure 10. Boiler Arrangement at Fort Knox.

Louisiana Army Ammunition Plant

The boiler room at the Louisiana Army Ammunition Plant's S-1604 contained three identical 300 hp Scotch Marine 1975 boilers manufactured by Superior Boiler Works of two-pass design. The boilers were equipped (in 1981) with Industrial Combustion Model D Hev-E-Duty power burners for both natural gas and No. 2 oil firing. Although the boilers were equipped for both gas and oil firing, oil was not used. The oil tank was kept empty and was not available for field tests. A portable oil tank, however, was easily connected to the main oil supply line. The steam from the boiler house was supplied mostly for production processes and the boiler operated with nearly 100 percent makeup water. Figure 11 shows the arrangement of the boilers in the boiler room. The new Century Controls O_2/combustible trim controller was tested on boiler No. 2; and test boiler No. 1 was left in its original configuration. Preparations at the Louisiana boiler house for field testing included the following:

1. Installing the new trim controller on boiler No. 2 per manufacturer's specifications
2. Installing individual gas flow meters
3. Installing individual and total oil flow meters
4. Providing openings in each stack for gas composition and temperature measurements
5. Modifying steam piping to allow steam venting
6. Modifying oil supply piping to allow portable tank hookup
7. Cleaning all three boilers.

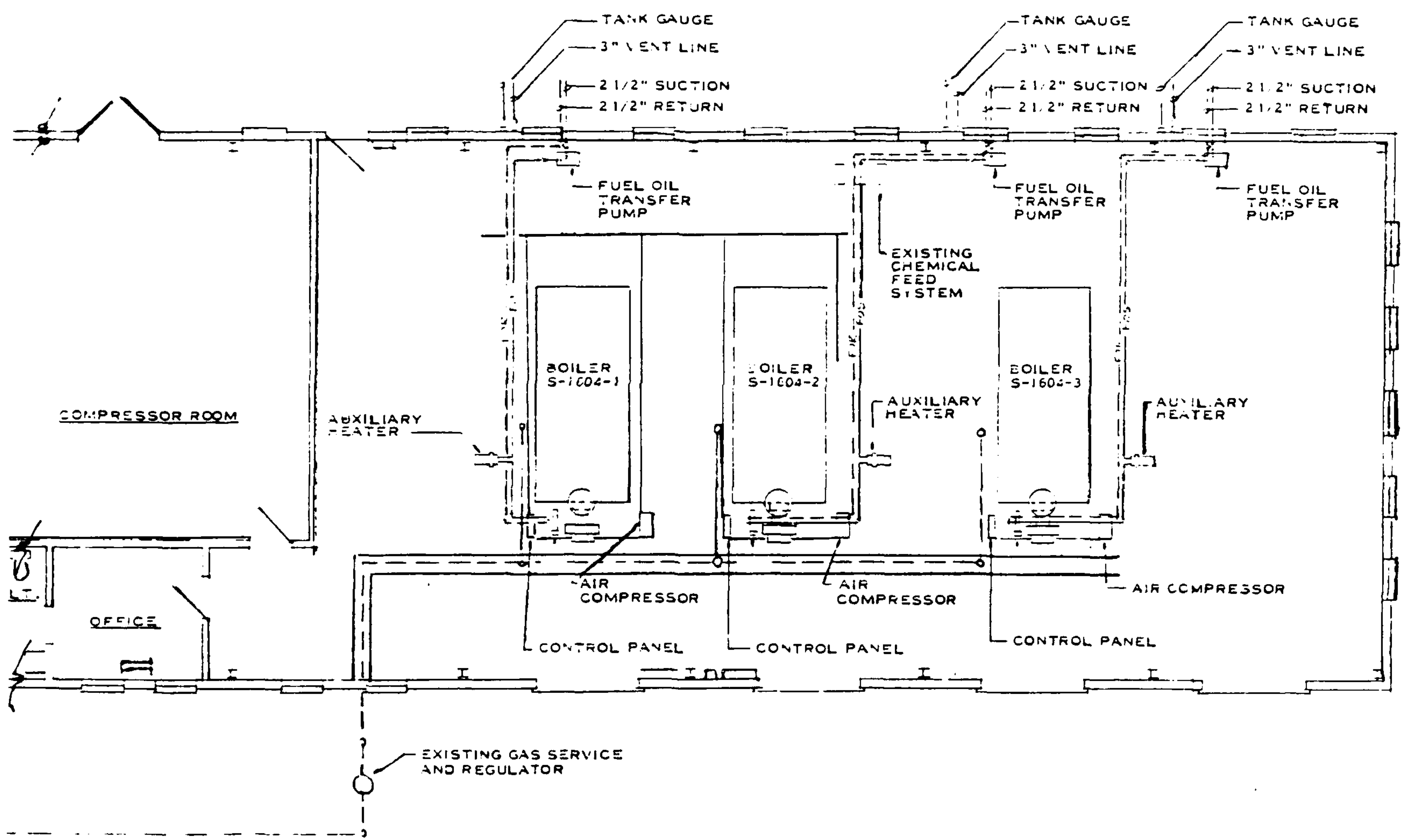

Figure 11. Boiler Arrangement at Louisiana Army Ammunition Plant.

8 SUMMARY AND RECOMMENDATIONS

Summary

The combustion control systems survey verified that the implementation of a combustion control system on a small dual-fuel package boiler is feasible and could result in improved boiler efficiency. The survey identified three groups of control systems, which differ from each other primarily in the hardware that generates the primary input signal to the microprocessor-based controller. This hardware includes:

- in situ O_2 analyzer
- ex situ O_2 or O_2/combustibles analyzer
- combustion air and fuel metering.

The first two groups (in situ and ex situ) operate on the principle of the fuel cell, where the measuring cell is zirconium oxide. In the in situ, the measuring cell is located inside the flue, where it analyzes the hot flue gas flowing past it. In the ex situ analyzer, a small sample of the flue gas is drawn from the flue to the heated cell housing outside the flue. The gas sample passes across the measuring cell and is then returned back to the flue. In addition, the ex situ system can incorporate, in the same cell housing, a catalytic-type sensor that can be used to measure the total combustibles.

Various claims are made for the superiority of one method over the other. The in situ reportedly has shorter response time, while the sample transport in the ex situ system produces a slightly longer time constant. Other comparisons can be based on ease of replacement and cost of the measuring cell(s). It is claimed that the ex situ cell(s) replacement is simpler and less costly than the in situ cell since it is located on the outside of the flue. In comparison, the in situ technique has a lower operating temperature range (1300 to 1600 °F) than the ex situ method, which can operate at temperatures as high as 3200 °F.

The third technique controls combustion by a system that measures the flow of the combustion air and fuel before it enters the burner of the boiler, thus eliminating a need for the analyzer. Air and fuel flows are measured by the differential pressure transducers installed in the air and fuel supply lines. Since no component of the system is exposed to elevated temperatures, the cost associated with the system maintenance should be minimal.

The microprocessor based controllers offered by manufacturers are state-of-the-art electronic control devices. These are, in a sense, special purpose computers that use the difference between the desired value and the actual value of a control variance (oxygen in the flue) to eliminate the error in the actual value. The method that these controllers use to counteract this deviation from the setpoint differs from one controller to another. The controllers identified in the first group of control systems are mostly of a single-loop design, either: proportional; proportional integral; proportional, integral, derivative; or time proportioning. One of the controllers in this group (Syconex) includes in its strategy a self adaptive control that automatically adjusts the usually fixed parameter (O_2 level per given firing rate) to optimize the loop response. The other controllers (Dynatron, Westinghouse, and Ametek) use a less complicated programmed adaption system where O_2 level per given firing rate is programmed into the controller, therefore producing a predictable effect on the gain of the control loop.

The second group of control systems are multivariable systems. The systems consist of a series of basic control loops connected together. Both of the systems listed (Century Controls and Ametek) are of time-proportioning design where the controller operates for a predetermined length of time, then stops and waits for another preprogrammed period. Both the on and off time periods are adjustable.

The third group, represented by Control Techtronics, uses a control system based on the principle of the ratio controller. Ratio control systems maintain a relationship between two variables (combustion air and fuel) to provide regulation of a third variable (excess O_2).

The actuators of the control systems are the final controlling elements of the systems. The actuators vary in size, mechanical design, output torque, and manner of incorporating (linking) with the existing boiler control components.

Recommendations

To quantitatively identify the benefit of the combustion control system when installed on a package boiler, a field test program should be initiated. The test program should include three combustion control systems, or one system from each of the three groups of the combustion controls identified in the conclusions of this project. The three controls should be installed on three existing boilers and their performance monitored. The test program should be scheduled as follows:

1. Short-term performance testing (about 1 week). During this time, a full set of data would be obtained at various firing rates to identify the potential benefit of the control system on the boiler operation.

2. Long-term operation testing (6 months to 1 year). During this period, the combustion data would be periodically obtained and the control system evaluated as to its stability, accuracy, maintenance, etc.

3. Short-term performance testing (about 1 week). A full set of data would again be collected and compared with the data obtained at the beginning of the test program.

The following combustion control systems are recommended for the field test program:

- Century Controls, O_2/Combustible Trim Controller
- Control Techtronics, Combustion Air/Fuel Ratio Controller
- Westinghouse, O_2 Trim Controller.

METRIC CONVERSION TABLE

1 in.	=	25.4 mm
1 ft	=	0.305 m
1 sq ft	=	0.093 m^2
1 lb	=	0.453 kg
1 gal	=	3.78 L
1 psi	=	6.89 kPa
°F	=	(°C × 1.8) + 32
1 hp	=	33.479 Btu/hr

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APPENDIX: Combustion Control Systems and Instrumentation Manufacturers

Air Monitor Corporation
1050 Hopper Avenue
Santa Rosa, CA 94501
707/544-2706
ATTN: Mr. Ken DeBaun

Ametek, Thermox Instrument Division
150 Freeport Road
Pittsburgh, PA 15238
412/828-9040

Anacon Div., High Voltage Engr. Corporation
RAECO, Inc.
550 Armory Drive
South Holland, IL 60473
708/331-62001
ATTN: Mr. Ron Ektrom

Analytical Products Division
Sybron Corporation
110 River Road
Des Plaines, IL 60016

Anarad, Inc., Delta Instrument Sales
603 North Court Street, Suite 260
Palatine, IL 60067
708/934-8328
ATTN: Mr. Nat Rogers

Astro Analytical Corp.
100 Park Avenue
League City, TX 77573
713/332-2484

Bailey Controls Co., Division of Babcock & Wilcox
Fred Kramer & Associates Inc.
115 Lively Boulevard
Elk Grove Village, IL 60007
708/593-0010

Bambeck Systems, Inc.
P.O. Box 41070
7005 Mill Road
Cleveland, OH 44141
216/526-7070
ATTN: Mr. Lester Gress

Century Controls, Inc.
750 South Plaza Drive
St. Paul, MN 55120
612/454-0792

Control Techtronics, Inc.
99 S. Cameron St.
Harrisburg, PA 17101-2805
717/238-0405
ATTN: Mr. John S. West, President

Cosa Instrument Corp.
70 Oak Street
Norwood, NJ 07648
201/767-6600

Dynatron, Inc., Energy Conservation Systems
P.O. Box 745
Wallingford, CT 06492
203/265-7121
800/362-3124
ATTN: Mr. J. Cognetta

Honeywell Process Control Div.
1100 Virginia Drive
Fort Washington, PA 19034
215/641-3000
800/328-5111

ITT General Controls Division
PO Box 68311
Schaumberg, IL 60168-0311
708/240-2488
ATTN: Mr. Chuck Grinston

Land Combustion, Inc.
115 Springwell Lane
Paducah, KY 42001
ATTN: Mr. A. L. Joyner

Lear Siegler, Inc.
2400 E. Devon Avenue, Suite 318
Des Plaines, IL 60018
708/296-5040
ATTN: Mr. Dave Joseffer

Leeds And Northrup
680L Joliet Rd.
Willowbrook, IL 60521
708/789-0063

Measurex Corporation
One Results Way
Cupertino, CA 95014
408/255-1500

Milton Roy Company, Flow Control Division
201 Ivyland Road
Ivyland, PA 18974
215/441-0800

North American Mfg. Co.
4455 East 71st St.
Cleveland, OH 44105
216/271-6000

Pyronics Inc., Soper Cliff Company
513 Loves Park Drive
Rockford, IL 61111
815/633-8230

Rosemount, Inc.
2505 Finley Road Ste 110
Lombard, IL 60148
708/495-8383
ATTN: Mr. Bob Arcaro

J.W. Sweet Company
P.O. Box 70
Chapin, SC 29036
803/345-5553

Synconex Corporation, Etc Division
433 W. Allen Avenue
San Dimas, CA 91773-1443
714/592-5684

Teledyne Analytical Instruments
Empro, Inc.
121 S. Lombard Road
Addison, IL 60101
708/629-3504
ATTN: Mr. Levan

Toshiba International Instrument Division
Memco Sales & Service Corp.
1331 Brummel Street
Elk Grove Village, IL 60007
708/228-9555
ATTN: Mr. Bob Folds

Westinghouse Electric Corporation
Combustion Control Division
1201 N. Main St.
Orrville, OH 44667
216/682-9010

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CMTC Hohenfels 09173
ATTN: AETTH-DEH
Mainz Germany 09185
ATTN: BSB-MZ-E
21st Support Command
ATTN: DEH (10)
US Army Berlin
ATTN: AEBA-EH 09235
ATTN: AEBA-EN 09235
SETAF
ATTN: AESE-EN-D 09613
ATTN: AESE-EN 09630
Supreme Allied Command
ATTN: ACSGEB 09703
ATTN: SHIHB/ENGR 09705

INSCOM
ATTN: IALOG-I 22060
ATTN: IAV-DEH 22186

USA TACOM 48397
ATTN: AMSTA-XE

Defense Distribution Region East
ATTN: DDRE-WI 17070

HQ XVIII Airborne Corps 28307
ATTN: AFZA-DEH-EE

4th Infantry Div (MECH)
ATTN: AFZC-FE 80913

Fort Pickett 23824
ATTN: AFZA-FP-E

Tobyhanna Army Depot 18466
ATTN: SDSTO-EH

US Army Materiel Command (AMC)
Redstone Arsenal 35809
ATTN: DESMI-KLF
Jefferson Proving Ground 47250
ATTN: STEJP-LD-F/DEH
Letterkenny Army Depot
ATTN: SDSLE-ENN 17201
Pueblo Army Depot 81008
ATTN: SDSTE-PUI-F
Dugway Proving Ground 84022
ATTN: STEDP-EN
Tooele Army Depot 84074
ATTN: SDSTE-ELF
Yuma Proving Ground 85365
ATTN: STEYP-EH-E
Tobyhanna Army Depot 18466
ATTN: SDSTO-EH
Seneca Army Depot 14541
ATTN: SDSSE-HE
Aberdeen Proving Ground
ATTN: STEAP-DEH 21005
Sharpe Army Depot 95331
ATTN: SDSSH-E
Fort Monmouth 07703
ATTN: SELFM-EH-E
Savanna Army Depot 61074
ATTN: SDSLE-VAE
Rock Island Arsenal
ATTN: SMCRI-EH
ATTN: SMCRI-TL
Watervliet Arsenal 12189
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ATTN: Library 20783
White Sands Missile Range 88002
ATTN: Library
Corpus Christi Army Depot
ATTN: SDSCC-ECD 78419

FORSCOM
ATTN: Facilities Engr (12)
Fort Bragg 28307
ATTN: AFZA-DE
Fort Campbell 42223
ATTN: AFZB-DEH
Fort McCoy 54656
ATTN: AFZR-DE
Fort Stewart 31314
ATTN: AFZP-DEF
Ft Buchanan 00934
ATTN: Envr Office
Ft Devens 01433
ATTN: AFZD-DE
Fort Drum 13602
ATTN: AFZS-EH-E
Fort Irwin 92310
ATTN: AFZJ-EH
Fort Hood 76544
ATTN: AFZF-DE-AES Engr
Fort Meade 20755
ATTN: AFKA-ZI-EH-A

6th Infantry Division (Light)
ATTN: APVR-DE 99505
ATTN: APVR-WF-DE 99703

National Guard Bureau 20310
ATTN: Installations Div

Fort Belvoir 22060
ATTN: CETEC-IM-T
ATTN: CECC-R 22060
ATTN: Engr Strategic Studies Ctr
ATTN: Australian Liaison Office

USA Natick RD&E Center 01760
ATTN: STRNC-DT
ATTN: DRDNA-F

TRADOC
ATTN: DEH (13)
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Carlisle Barracks 17013
ATTN: ATZE-DIS
Fort Eustis 23604
ATTN: DEH
Fort Chaffee 72905
ATTN: ATZR-ZF
Fort Sill 73503
ATTN: ATZR-E

US Army Materials Tech Lab
ATTN: SLCMT-DEH 02172

WESTCOM 96858
ATTN: DEH
ATTN: APEN-A

SHAPE 09705
ATTN: Infrastructure Branch LANDA

Area Engineer, AEDC-Area Office
Arnold Air Force Station, TN 37389

HQ USEUCOM 09128
ATTN: ECJ4-LIE

AMMRC 02172
ATTN: DRXMR-AF
ATTN: DRXMR-WE

CEWES 39180
ATTN: Library

CECRL 03755
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USA AMCOM
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ATTN: AMSMC-IR 61299
ATTN: Facilities Engr (3) 85613

USAARMC 40121
ATTN: ATZIC-EHA

Military Traffic Mgmt Command
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ATTN: MT-LOF 20315
ATTN: MTE-SU-FE 28461
ATTN: MTW-IE 94626

Fort Leonard Wood 65473
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ATTN: ATZA-TE-SW
ATTN: ATSE-CFLO
ATTN: ATSE-DAC-FL

Military Dist of WASH
Fort McNair
ATTN: ANEN 20319

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Norton AFB 92409
ATTN: Library

US Army ARDEC 07806
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Charles E Kelly Spt Activity
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Engr Societies Library
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Defense Nuclear Agency
ATTN: NADS 20305

Defense Logistics Agency
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Walter Reed Army Medical Ctr 20307

US Military Academy 10996
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ATTN: Facilities Engineer
ATTN: Geography & Envr Engrg

416th Engineer Command 60623
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USA Japan (USARJ)
ATTN: APAJ-EN-ES 96343
ATTN: HONSHU 96343
ATTN: DEH-Okinawa 96376

Naval Facilities Engr Command
ATTN: Facilities Engr Command
ATTN: Division Offices (11)
ATTN: Public Works Center (8)
ATTN: Naval Constr Battalion Ctr 93043
ATTN: Naval Civil Engr Laboratory (3) 93043

8th US Army Korea
ATTN: DEH (12)

US Army HSC
Fort Sam Houston 78234
ATTN: HSLO-F
Fitzsimons Army Medical Ctr
ATTN: HSHG-DEH 80045

Tyndall AFB 32403
ATTN: AFESC Program Ofc
ATTN: Engrg & Srvc Lab

Chanute AFB 61868
ATTN: 3345 CES/DE

USA TSARCOM 63120
ATTN: STSAS-F

American Public Works Assoc 60637

US Army Envr Hygiene Agency
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US Gov't Printing Office 20401
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